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SATELLITE WEATHER RECONNAISSANCE*

S. M. Greenfield and W. W. Kellogg

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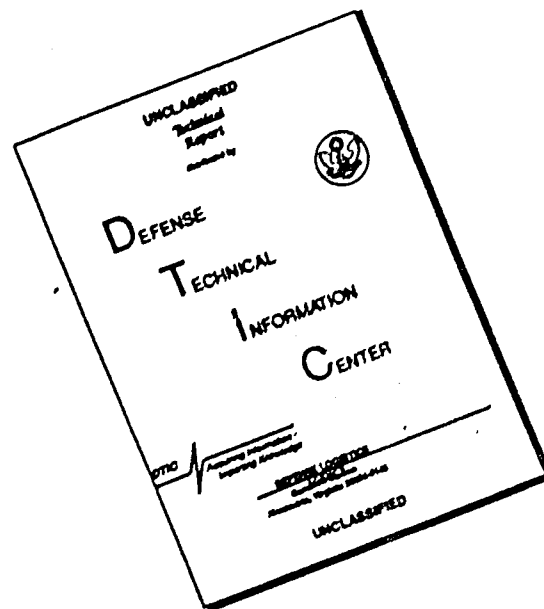
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S. M. Greenfield and W. W. Kellogg

ABSTRACT

Various aspects of weather reconnaissance by satellites including limitations, capabilities relative to present methods, and growth potential are discussed. ()

INTRODUCTION

Meteorological factors must be considered carefully in planning many civilian and military operations. The meteorological information provided for this purpose can be either in the form of actual data concerning the present weather picture, or in the form of a forecast as to future conditions at the time of the operation. In either case, the information provided is only as good as the weather data available.

It is well known that there is in operation a world-wide weather data collection network supported by most of the civilized nations of the world. Furthermore, these data are freely disseminated to all nations participating in this collection program. While this appears to be a great wealth of data, it is also apparent that there are large areas of the world (e.g. the oceans and the polar regions) from which very limited data are forthcoming. The only means presently available for filling the gaps in these data are weather reconnaissance by aircraft, or the positioning of a small number of weather observing ships. At best, even with such a great effort, this provides spatially spotty information, and by its very nature the system lacks the one

quality of observation most necessary to synoptic meteorology, that of continuity in time and space.

A third possibility, however, has been suggested⁽¹⁾⁽²⁾⁽³⁾ that might indeed contain the gap-filling ability called for. This is weather reconnaissance by means of satellites. The questions that one might ask about such a system are:

1. What are the limitations of such a system?
2. Within these limitations, what weather information is obtainable, and is it adequate to do the job?
3. What is the growth potential of a satellite reconnaissance system?
4. Can this information be fitted into the present weather system?

THE LIMITATIONS OF SATELLITE RECONNAISSANCE

The limitations of satellite weather reconnaissance are brought about by the uniqueness of the types of observations that can be made from such a vehicle. Initially, useful weather observation from a satellite will be obtained mainly by optical means. That is, our initial observations will consist of "looking down" at the visible manifestations of weather. The first attempt to do this is planned for the I.G.Y. satellite program, and William Stroud and his associates at the Signal Engineering Laboratories have already developed a simple scanning system for the Vanguard satellite.

It is obvious that in simply observing the weather through the "eye" of a high-altitude robot almost all of the regular quantitative measurements usually associated with synoptic meteorology tend to fall by the wayside. It is impossible to make more than an intelligent guess at

the values of temperature, pressure, humidity, and the remaining conventional meteorological parameters.

Using this type of data as the sole source on which to base a weather analysis is almost completely foreign to the normal experience of the synoptic meteorologist. The basic limitation to weather satellites, then, is the degree to which meteorologists can apply what will initially be qualitative information to the science of synoptic weather analysis. Clouds, being the objects most discernible from extreme altitudes, become the important item of observation and must be utilized to the utmost in forming a synoptic picture. It is apparent that from clouds alone it will be impossible to tell everything about the current synoptic situation.

Considered, however, with both theoretical knowledge and that gained through experience, an accurate cloud analysis can produce surprisingly good results in areas where no information is available. Further, in areas where good synoptic data are currently obtained from the surface, satellite cloud observations give a continuity or completeness that is not presently available.

WEATHER INFORMATION OBTAINABLE FROM SATELLITES

Recognizing that cloud observations will initially be the major output from a satellite weather reconnaissance vehicle, it is logical to ask two basic questions. First, is there any difficulty in seeing and/or identifying clouds from these altitudes? Second, what synoptic data can actually be obtained from these observations?

The Visibility of Clouds from Satellites

A past report by RAND⁽¹⁾ considered this problem. Utilizing Hewson's work⁽⁴⁾⁽⁵⁾ on diffuse reflection coefficients for clouds of various

thicknesses and the following definition of contrast, the results presented in Fig. 1 were obtained for daylight conditions.

$$\text{Contrast, } C = \frac{\rho_b - \rho_d}{\rho_b}$$

where

ρ_b = brightness (albedo) of the brightest thing viewed
(either object or background)

ρ_d = brightness of darkest object viewed (albedo)

C = contrast between the two

From a knowledge of background albedos (less than .4 for most surfaces) it is possible to show that, except in the case of new or old snow and for low solar elevations over a water surface, the contrast between clouds and background would be greater than 40 per cent.

A contrast greater than 40 per cent appears usable from the standpoint of most television or photographic equipment visualized for satellite. It is interesting to note that the majority of observations will be made under the influence of an oblique sun. Due to this fact, even in the case of high albedo backgrounds over land, the clouds will be seen imaged against their own shadows, which will once again provide a usable contrast.

The usefulness of a given attainable contrast is intimately tied up with the desired ground resolution. In the case of cloud photography it is found that useful information can be obtained with quite poor resolution. For example, gross cloud cover can certainly be obtained with the ability to resolve ground dimensions of the order of one mile or greater. To have the ability to identify cloud types, it has been found by studying cloud pictures such as Fig. 2 taken from rockets,⁽¹⁾ that it is necessary to resolve ground dimensions of the order of 500 to 1000 ft. Such resolution

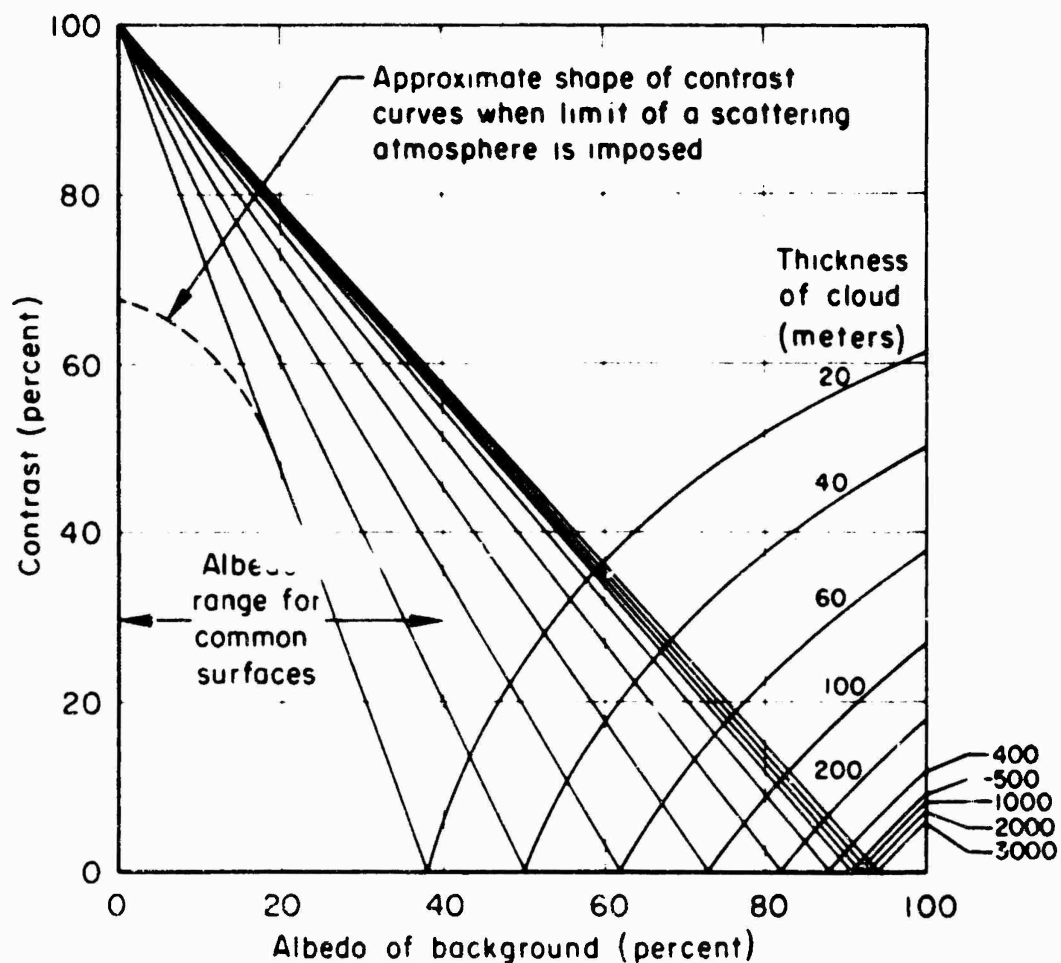
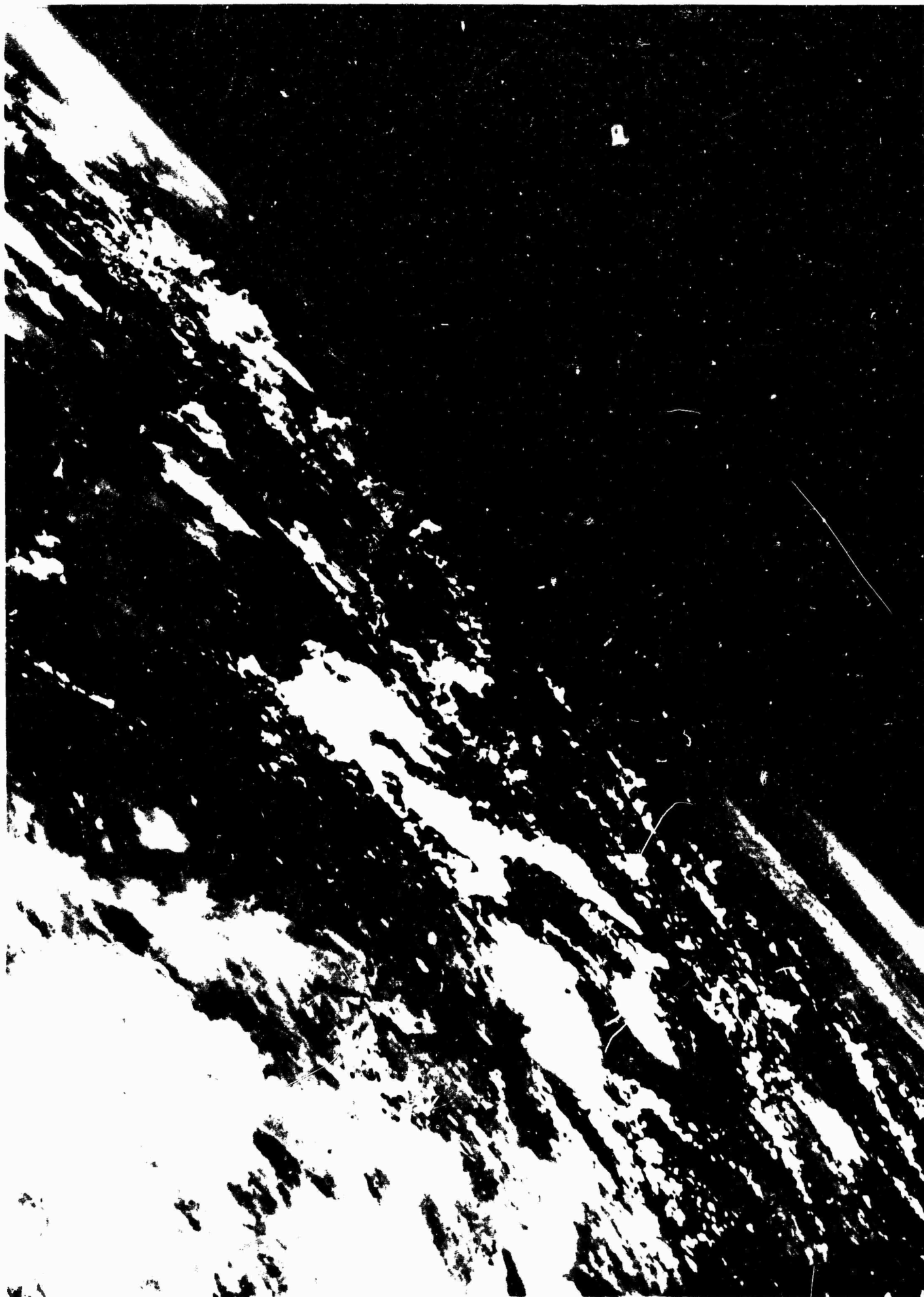


Fig.1—Available contrast with varying cloud and background albedos



(Official U.S. Navy John Hopkins (APL) photograph)

Fig. 2— V-2 No. 40, July 26, 1948. Maximum altitude 60.3 mi
View looking WSW towards Mexico and Gulf of California

is certainly attainable with present TV and optical systems and would not require an exorbitant bandwidth in the radio link to the ground.

On the basis of the above statements, it is felt that the problem of recognition and identification of clouds is not a limitation on satellite weather reconnaissance.

What Can Be Obtained from Satellite Weather Observations

Cloud observations from a satellite could allow the synoptic meteorologist to view the entire weather pattern in a way that he can hardly achieve by present indirect methods. That is to say, the synoptic meteorologist today plots the instantaneous weather information from many points on world or hemisphere maps and then proceeds to analyze it in a form that will provide a complete picture of the weather over large areas. It is obvious that, since specific cloud families are associated with particular meteorological phenomena, a cloud picture of a large area of the world will provide a knowledgeable person with a crude but complete weather map.

Even if this were the only information forthcoming from a satellite, it might by itself be worthwhile, since in areas where good observations were available it would provide a completeness of weather pictures that is just not possible from point observations alone. Further, in large uninhabited or inaccessible areas it would provide a continuity that, with the help of peripheral weather information, would allow the meteorologist to fill in the blank areas on his weather map with more certainty.

In addition to this gross picture, however, there is a great deal more information that can be extracted from cloud photographs.⁽¹⁾ Wind direction may be estimated in several ways. First, from the present meteorological models it is established that certain definite weather situations will

produce certain sequences of clouds preceding or following them. This will tend to orient the situation with respect to the ground. Once this orientation has been established, the wind direction may be approximated through a knowledge of the theoretical circulation associated with a given synoptic weather situation. Second, since cumulonimbus clouds extend from as low as 1600 ft up to 40,000 ft, their slope becomes a good indication of wind shears. Third, there is the formation of cumulus clouds on the lee side of mountains. Fourth, the direction of movement of atmospheric pollutants such as industrial gases, etc., will indicate the direction of winds at low altitudes.

Temperatures may be estimated by starting with the statistical normal for that time of year. This first estimation may then be modified by the various affecting conditions. Cloud systems, wind direction, and even forms of general cover (snow, etc.) will aid the analyst in deciding whether the area under observation is being affected by relatively cold or warm air. Upper air temperatures may be estimated in the same manner, clouds indicating the boundary between air masses (fronts). The slopes of vertically developed cloud forms will also aid in determining the temperature gradient of the surrounding area.

It is apparent that no quantitative values of pressure are forthcoming from an analysis of observations of these types. Furthermore it is virtually impossible even to make a quantitative estimate, other than to state whether the area is under the influence of a high- or a low-pressure system.

COVERAGE AND CONTINUITY

In previous sections of this paper, it was stated that, given the ability to record and identify clouds, it appeared possible to make a fair

estimate of the occurring weather situation. An important question that still must be answered is the question of continuity. That is to say, weather being a dynamic phenomenon, the ability to forecast its development depends upon the ability to observe its behavior repeatedly. For most weather phenomena, the maximum allowable cycling time is of the order of 24 hours. The question then is: can 24-hour continuity be established with satellite observations?

To answer this question let us assume that the location and movement of low-pressure systems constitute the most valuable piece of weather information. Let us further recognize that low-pressure systems are characterized by their associated cloud systems. On this basis it should be possible to examine the probability of detecting this type of weather situation as a function of time.

To do this we shall make several simplifying assumptions. First, it will be assumed that the clouds associated with a cyclonic system cover an area at least 400 mi across and can be represented by a square configuration. Second, we shall assume that a system can be detected if even a small part of its cloud system comes within viewing range of the satellite. Although this last assumption appears to be somewhat questionable, it becomes more reasonable if we remember that there will be some measure of day-to-day synoptic continuity established.

When the cloud square just touches the edge of the viewing path, the system can no longer be seen. Figure 3 illustrates this (Storm A). It will be noted that the width of the viewing path chosen in this example is also 400 mi, and the satellite altitude is 300 mi. We can say, then, that in this case a storm can be seen when the center of its associated

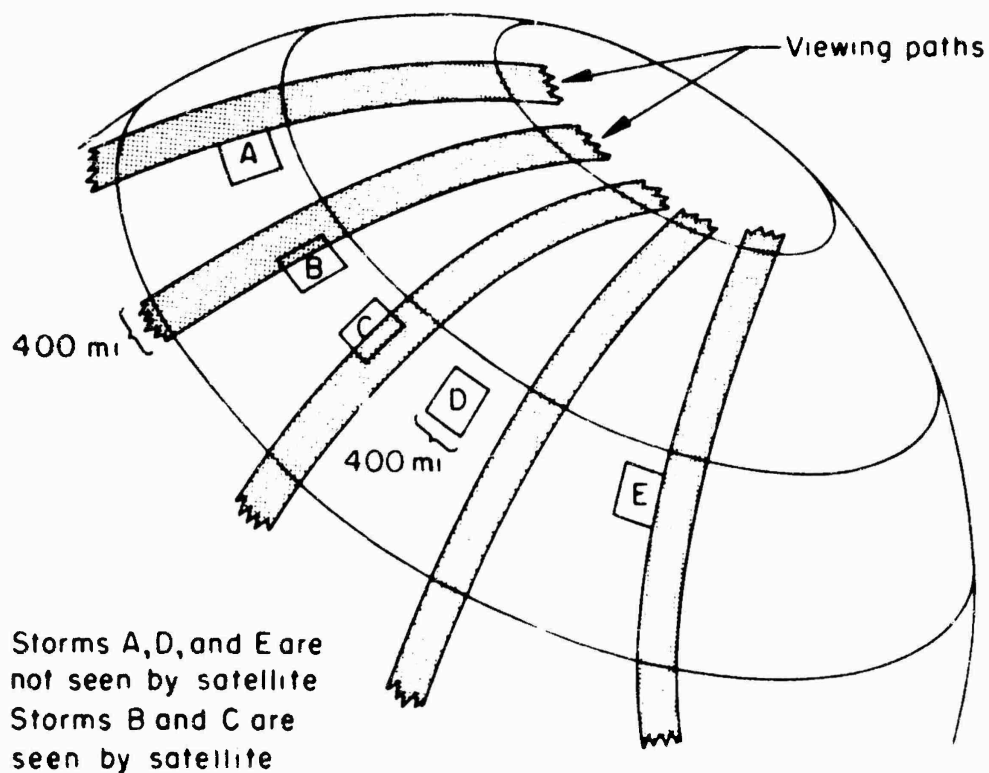


Fig. 3— Schematic illustrating relation between storm location and satellite path. Satellite inclination is 83° .

cloud system lies within 400 mi of the centerline of any one path. Due to the relatively slow movement of a storm, when compared with the progression rate of successive passes of the satellite, the movement of a storm between successive passes (1 1/2 hours apart) can be neglected.

Keeping in mind the fact that the successive passes are evenly spaced in longitude, we can now write down an expression for the probability that a storm will be seen at least once a day:

$$P_{\phi} = \frac{N(W_p + W_c)}{D_{\phi}}$$

where N is the number of passes within a distance D_{ϕ} measured along a given latitude, ϕ is the latitude of the center of the storm system, W_p is the width of the viewing path, and W_c is the width of the cloud square. Using the values of $W_c = 400$ mi and $W_p = 400$ mi, P_{ϕ} has been computed and is presented in Fig. 4. As can be seen, the probability of detecting a 400-mi-wide storm anywhere in the U.S. is greater than about 60 per cent, the probability increasing toward the latitude of tangency (in this case 85°N). For the sake of comparison, a curve representing a storm width of 100 mi has been plotted on the same figure. In this case, the minimum probability decreases to approximately 35 per cent. However, the average cyclonic storm system is at least 400 mi across, and some are as large as 1000 mi.

Although these probabilities are fairly good, it is understandably more desirable to achieve 100 per cent coverage if possible. Figure 4 also shows a plot of the probability of detection with a path width equal to 1200 miles. It is interesting to note that this 1200 mile strip width can be achieved with the same satellite viewing system as used for the 300-mile-altitude,

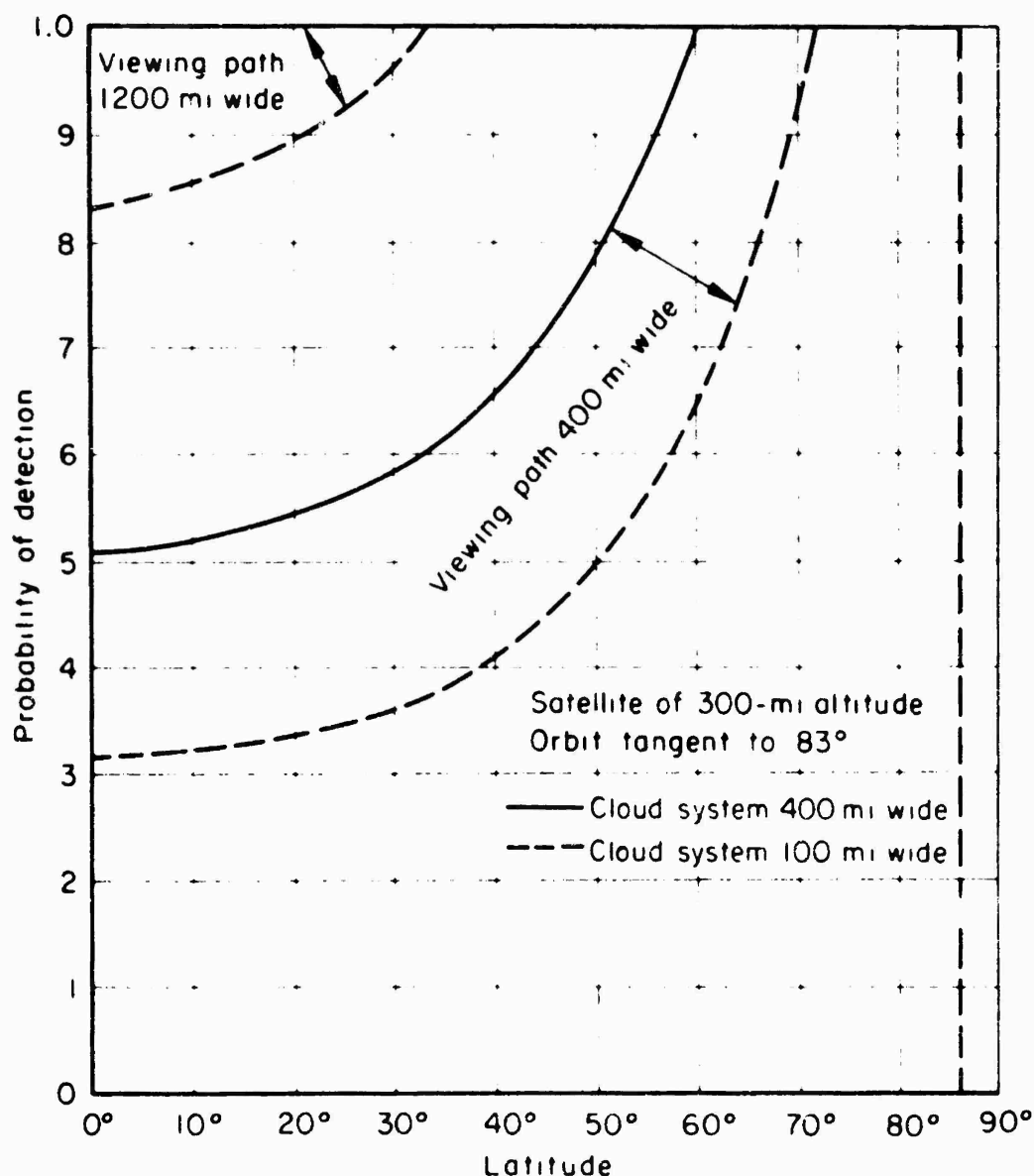


Fig 4 — Probability on a given day of detecting a cloud system (associated with a specific weather situation) centered at a given latitude

400-mile-strip-width vehicle. This is accomplished by increasing the altitude of the satellite by a factor of 3 (to approximately 1000 miles). This, however, results in a degradation of resolution by this same factor of 3. It is seen, then, that it is possible to achieve 100 per cent coverage of a given area with a somewhat poorer resolution.

On the basis of this analysis, it appears feasible to conduct weather reconnaissance from a satellite, at least from the standpoint of contrast, resolution, area coverage, and continuity.

THE POTENTIAL OF FUTURE WEATHER SATELLITES

As satellites - and our ability to control and keep track of them - improve, it appears certain that we can expect an equivalent improvement in the expected weather data. The improvement will probably be in the direction of more quantitative information on the atmosphere. For example, if we can accurately determine the height, position, and velocity of a satellite as a function of time, then it appears feasible to determine the height of clouds viewed, which would be of some use to the meteorologist. This might be done as follows:

At a time t_1 a vertical picture is taken of the surface. (It is assumed to be possible to determine the vertical direction in the satellite.) By reference to this known vertical, a cloud directly below the satellite is chosen. At a time t_2 a second vertical picture is taken which includes the chosen cloud. The angle off the vertical to this cloud in the second picture is measured. This configuration is illustrated in Fig. 5, which identifies the various angles and distances. It can be seen that, by the law of sines,

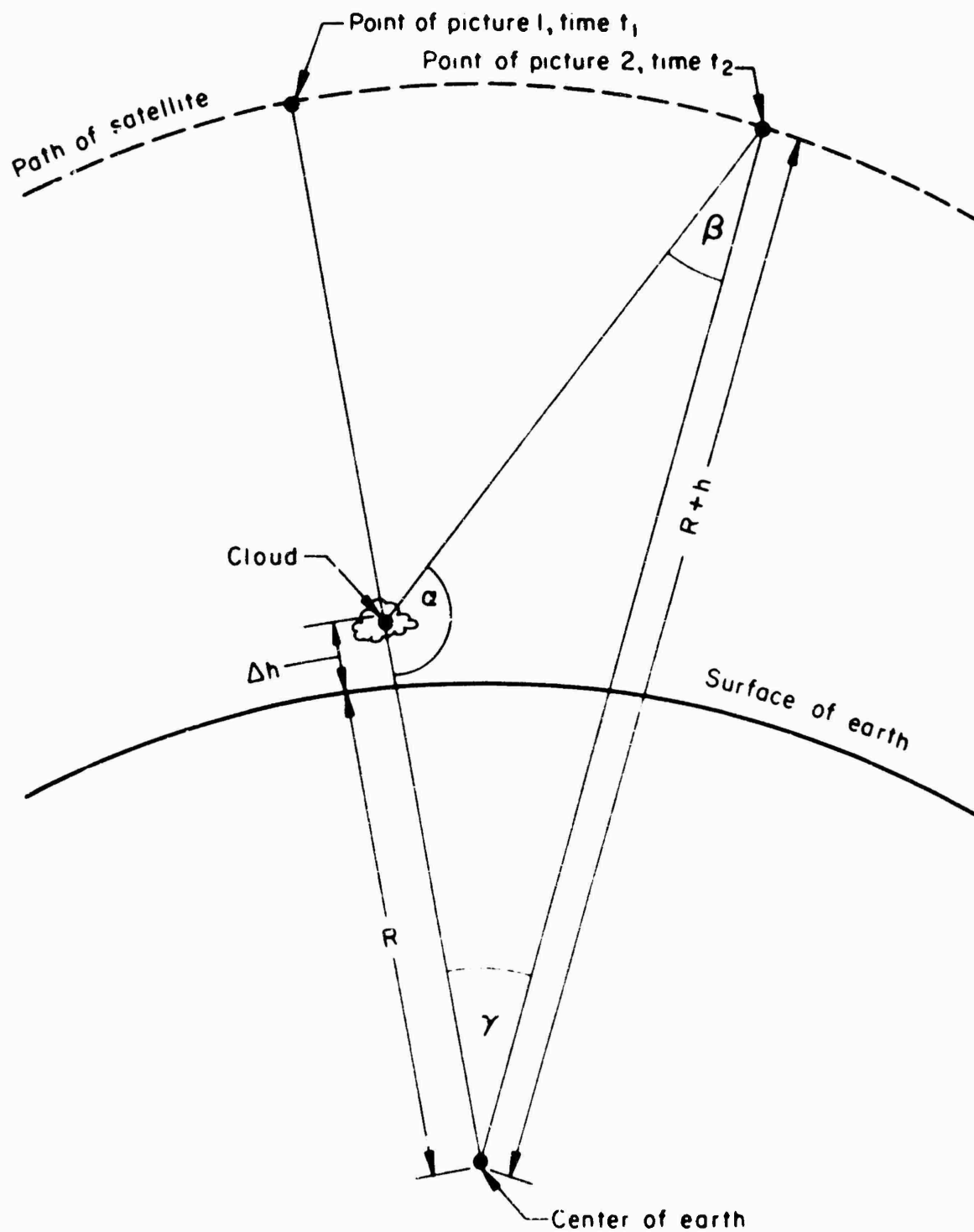


Fig.5 — Configuration for cloud height determination

$$\frac{R + \Delta h}{\sin \beta} = \frac{R + h}{\sin \gamma} = \frac{R + h}{\sin \gamma \cos \beta + \cos \gamma \sin \beta}$$

and

$$R + \Delta h = \frac{R + h}{\sin \gamma \cot \beta + \cos \gamma}$$

Since γ is equal to $\frac{V \Delta t}{R+h}$, where V is the velocity of the satellite and Δt is equal to $(t_2 - t_1)$,

$$\Delta h = \text{height of the cloud} = R \left[\frac{1}{\sin \left(\frac{V \Delta t}{R+h} \right) \cot \beta + \cos \left(\frac{V \Delta t}{R+h} \right)} - 1 \right] + \frac{h}{\sin \left(\frac{V \Delta t}{R+h} \right) \cot \beta + \cos \left(\frac{V \Delta t}{R+h} \right)}$$

Since R , h , V , Δt , and β are known, Δh is completely determined.

Widger and Touart⁽²⁾ and the Technical Panel for the Earth Satellite Program⁽⁶⁾ have suggested other quantitative information, in addition to cloud cover, that might be obtained from a more sophisticated satellite. These are:

1. Total moisture content. By measuring the intensity of the reflected radiation at two adjacent wavelengths in the near infrared, one of which is not absorbed by water vapor and the other of which is partially absorbed, the total amount of water vapor in a column of the atmosphere in which there are no clouds can be determined.
2. Total ozone content. Utilizing somewhat different wavelengths than those for moisture, the total ozone content can be determined.

3. Temperatures at or near the tropopause. By observing the radiation in the 6-micron absorption band in the vertical, it would be possible to measure the radiation emitted by the top of the tropopause, and hence to map the effective temperature of that region.
4. Temperatures at or near the top of the ozone layer. Similarly, measuring the emission at 9.6 microns would give the effective temperature in the top of the ozone layer, and would allow meteorologists to map the temperature in a part of the atmosphere usually inaccessible to balloons.
5. Total radiation. The total infrared and solar radiation flux being absorbed, reflected, and emitted by each part of the earth is of great theoretical importance, since it is the balance between these inputs and outputs which determines the heat budget of the atmosphere - now only roughly estimated. This type of observation is relatively easy to do, and has already been developed for the I.G.Y. satellite program by Verner Suomi of the University of Wisconsin.
6. Radar measurements. Radars operating at wavelengths of the order of 3 - 10 cm could possibly give information on precipitation areas.

It should be noted that measurements (1) and (2) might also be accomplished by placing strong known sources of radiation at the surface and observing these from satellites at wavelengths of known water vapor and ozone absorption.

In addition to the above measurements it should also be possible to

measure the variation in solar radiation reaching the earth's atmosphere, particularly the radiation in the ultraviolet and X-ray region, which cannot be observed from the ground. As in the case of many of the suggested "advanced satellite" measurements, the measurement of solar radiation would be of more interest initially as a research experiment than as a day-to-day assistance in weather forecasting. It is not too hard to visualize, however, that in the future the knowledge of our atmosphere and how it is influenced by energy input variations will be greatly improved. When this time occurs, such measurements as the variation of solar X-radiation, the variation of heat input to the atmosphere (heat balance), etc., will indeed serve as forecasting tools.

DISSEMINATION OF SATELLITE WEATHER DATA

It is obvious that just having a satellite that provides useful weather information does not guarantee the usability of these data by the various meteorological services. Weather data, after all, are a perishable item. That is to say, the usefulness of a particular item of weather information decreases very rapidly with time after it is first obtained. For this reason it is important to provide a mechanism for putting the satellite data, in a usable form, into the data dissemination network as rapidly as possible.

For maximum usability, an appropriate maximum time delay from the time of gathering the data to actual dissemination would probably be of the order of one hour. This sort of time delay suggests a rather elaborate pick-up and relay system. One might visualize a "satellite weather data center" where several specific tasks are accomplished. First, incoming data are subjected to the necessary special analysis⁽¹⁾ that will extract from

them the maximum amount of usable meteorological information and disseminate it immediately. Second, picture mosaics are constructed to show the over-all cloud coverage. These mosaics are also disseminated as rapidly as possible. What is apparent is that, for a satellite to have maximum usability for weather purposes, at least as much thought and effort will have to be put into the analysis and dissemination problem as will be put into the design of the actual vehicle.

CONCLUSIONS

This paper has attempted to show the applicability of satellites to meteorology. In summary, it appears practical for satellites to make useful additions to the weather data now being collected by the worldwide meteorological network. Initially, satellite data would be mainly qualitative and be concerned primarily with cloud types and patterns, but advanced satellites may be visualized which will provide quantitative data. In addition to providing assistance in the forecasting of daily weather, future satellites should also aid in research leading towards improvement of the operational assistance provided by the weather services.

Most of the ideas suggested in this paper have not been completely proved; some theoretical work in this direction is presently being carried out by the Air Force and The RAND Corporation, and the current I.G.Y. program will also provide a preliminary test of some of the ideas through the Signal Engineering Labs' cloud cover experiment and the University of Wisconsin's radiation balance experiment. Enough work has been done, however, to clearly indicate the desirability of the employment of satellites for weather reconnaissance. The first weather satellites to be flown will be exploratory, and as more experience is gained in the interpretation of the

radically new kinds of observations which they can gather their usefulness will grow. It is not inconceivable that in the not-so-distant future satellites may actually supplant a part of our present weather network.

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